High Efficiency Steam Turbine Packages for Concentrated Solar Power Plants

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Abstract

Parabolic trough systems are the most developed technology for Concentrated Solar Power (CSP) plants to date. Existing CSP plants have a maximum power output of less than 100MW and Siemens has delivered steam turbines for most of these plants. Considerably larger power outputs of 200 to 340 MW are required in current CSP plant projects. Siemens is developing products, systems and solutions for our customers, to meet their requirements. For the products, Siemens has developed a steam turbine generator, which covers the requirement of large outputs in CSP plants.

Because of high investment costs for the solar field and large variations of the heat source, the major customer requirements for turbines in CSP plants are high efficiency and operational flexibility.

Since the steam cycle specified by customers is a common reheat type, this is a typical application for a combined high pressure (HP)/ intermediate pressure (IP) steam turbine. Siemens has more than 40 years field experience with combined HP/IP steam turbines. Today, as part of the SST-5000 series the combined HP/IP steam turbine is applied in single- and multi-shaft combined cycle power plant (CCPP) configurations and in steam power plants (SPP) of up to 700 MW.

Steam parameters such as temperature and pressure required for CSP plants are lower than those of fossil fired power plants and higher than the parameters of nuclear power plants. As a supplier of both fossil and nuclear steam turbines Siemens experience covers also the CSP thermodynamic range.

This paper describes technology and performance of the SST-5000 series optimized for application in CSP of the 250 MW class.

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1 Introduction

It is beyond doubt that the growth of the solar thermal power industry is accelerating: Close to 1,000 MW net capacity are installed worldwide, producing more than 1.5 million megawatt-hours electricity per year, another 5,500 MW net capacity are under construction or development by 2014 [3].

From the various technologies using concentrated sunlight to generate electrical power, parabolic trough systems represent the most proven technology. As shown in Figure 1, the first parabolic trough systems have been in operation since 1984. Concentrated Solar Power (CSP) systems of 200 MW size and larger have been announced for the near future.

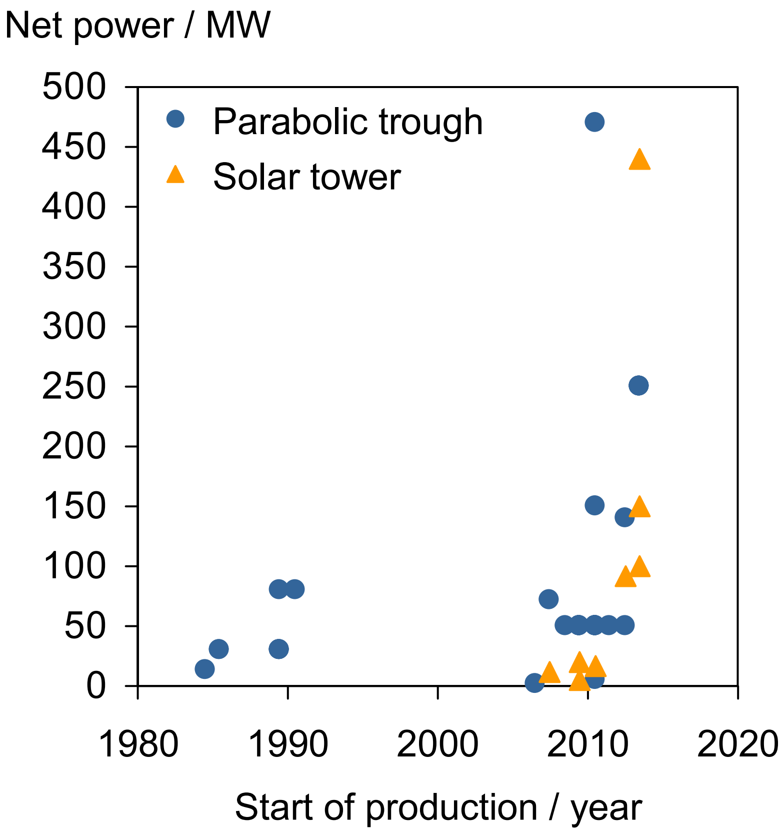

Figure 1: Production start vs. net power of parabolic trough and solar tower plants [3]

This paper focuses on steam turbine packages for large parabolic trough systems.

1.1 Vertically Integrated CSP Solutions

As shown in Figure 2, a CSP plant consists of mainly two major systems, the solar steam generator and the power block. The solar steam generator combines the solar field with its receivers, mirrors, structures and systems with the heat transfer fluid (HTF) piping, pumps and systems in order to produce steam, which is converted to electrical power in the power block. The core of the power block is the steam turbine package (steam turbine, generator, auxiliaries and systems), which is complemented by the balance of plant (water/steam cycle, cooling, civil, electrical equipment and further systems).

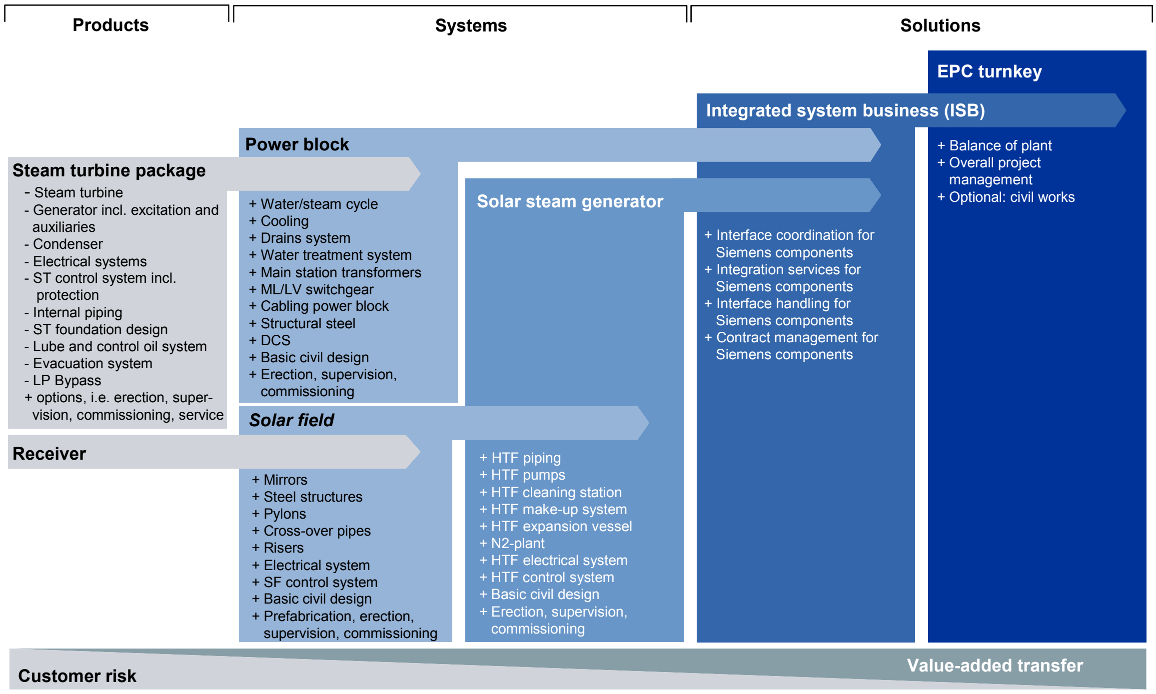

Figure 2: Products and systems of a concentrated solar power plant

These two main systems, the solar steam generator and the power block, need to be integrated in order to achieve maximum efficiency of the overall system. Siemens not only has the complete product portfolio in-house, but also extensive experience in integrating power components to a power block, solar components to a solar steam generator, and in integrating these two systems. In addition, Siemens offers full EPC (engineering, procurement, construction) turnkey solutions.

By reducing the number of suppliers, the customer significantly reduces the project realization risk. This one-stop-shop supply ensures the availability of all key components and systems and guarantees an optimum integration of all systems, resulting in maximum efficiency and lowest life-cycle-cost of the Concentrated Solar Power plant.

1.2 Customer Requirements

The development of the steam package for CSP takes into consideration the following main customer requirements:

Daily cycling

Solar power plants are subject to daily cycling by the nature of their power source – the sun does not shine 24 hours a day. This means that over the year 365 starts are required. Even if the thermal energy will be stored and used after sunset to extend the uptime of the power plant these storage systems are not yet dimensioned to provide energy for the full night period.

High flexibility and high efficiency in part load

The steam turbine may need to be capable of high and fast temperature and load transients due to frequent heat input changes caused by clouds. A currently investigated alternative to the use of HTF as heat transfer medium is the direct use of steam, which would lead to even faster load changes from clouds or solar irradiation changes.

Flexible feedwater preheating

To achieve 100% nominal plant power output over a wider range of the day / year, the solar field often is over-dimensioned with regard to the maximum steam turbine output, e.g. at 80% solar irradiation the steam turbine gets enough energy to produce 100% power output. If the solar energy exceeds this threshold (e.g. the 80%), instead of “blasting” it, one or more pre-heaters could be switched off, increasing the required heat flow to the water-/ steam cycle. Due to the residual bleeding steam in the turbine the power output will be increased (though with a lower water-/ steam cycle efficiency).

2 CSP Steam Cycle

The general water-/ steam cycle configuration for CSP plants is similar to usual steam power plants. A basic CSP flow chart is shown in Figure 3.

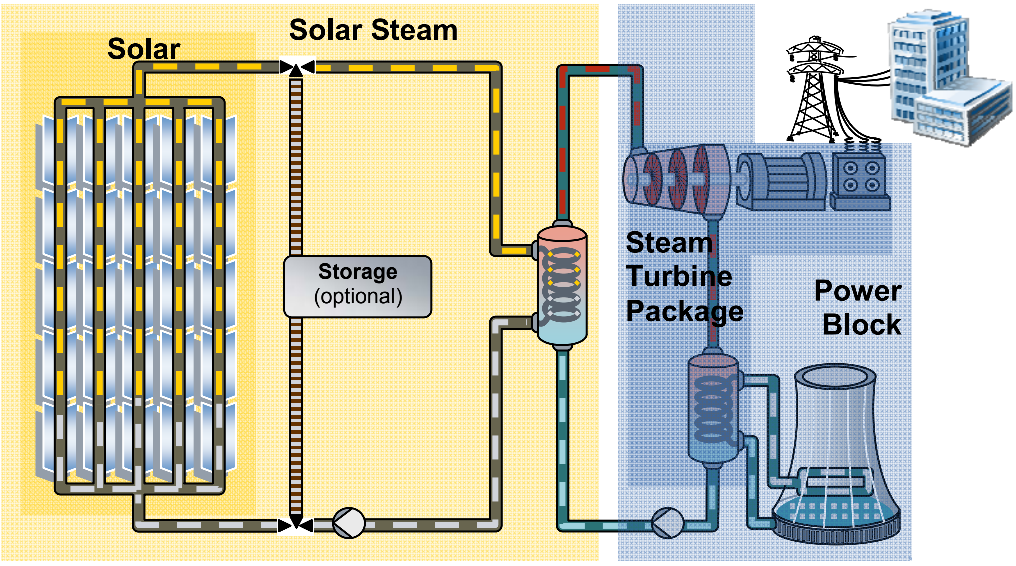

Figure 3: Main components of a CSP plant

Main steam coming from the steam generator is routed to the HP module of the steam turbine. After a first expansion in the HP module the steam will be superheated again in a reheater before entering the IP / LP turbine. At the outlet of the LP turbine the steam will be condensed and the condensate is pumped to the steam generator via preheaters. The preheaters are supplied with steam from turbine bleedings.

Significant differences to usual power plants are:

- Lower steam parameters
- Interaction of the solar circuit with the water-/ steam cycle
- Daily start up and shut down

Low steam parameters

The stability of typical heat transfer fluids (HTF) is limited to approximately 400°C, which is caused by their chemical properties. Following this temperature limitation in the solar field the maximum turbine inlet temperature is limited to approximately 380°C. But a low turbine

inlet temperature defines also the range of possible main steam pressures, as the moisture content at the outlet of different turbine modules should be chosen wisely.
Plant configurations with a larger heat storage system within the HTF cycle have a high erosion risk. In storage discharge mode the steam temperature is once again lower by approximately 12 – 15 K as there are additional terminal temperature differences. This leads to even higher moisture content at the turbine outlets. Some plants in Spain are equipped with a storage system which is designed for a capacity of 8 hours full load operation, so that this mode has to be considered for the plant design.

Besides the main steam and reheat pressure, various other parameters have to be designed for the storage discharge mode, for example the moisture separator capacity in the cold reheat line. The moisture separator reduces the erosion impact in the cold reheat system and increases the cycle efficiency slightly, because the droplets do not have to be evaporated again in the reheater.

A more complex improvement seems to be a double reheat concept. This would allow a slightly increased main steam pressure, reducing the moisture content at the end of the turbine expansions as well as increasing the overall efficiency due to a higher mean feeding temperature level. An additional advantage of the double reheat concept in comparison to conventional steam power plants is, that the heating medium can be pumped to the steam turbine as the heat exchangers are flexible in arrangement. This reduces the additional pressure losses on the steam side. Due to the low temperatures an additional turbine module after the second reheater is not necessary. The second reheater can be integrated in front of the LP turbine.

Interaction of the solar circuit with the water-/ steam cycle
The closed solar field circuit is connected to the water-/ steam cycle via the steam generator and reheater. In contrast to conventionally fired steam generators, the efficiency of the solar field is directly influenced by the design of the water-/ steam cycle. The ‘given’ hot HTF temperature and the pinch point situation determine the evaporation pressure in the steam generator. The evaporation pressure and the final feedwater temperature determine the HTF return temperature to the solar field. A higher HTF return temperature causes higher thermal losses in the solar field and requires more auxiliary power consumption for the HTF pumps in the solar field, as the circulating HTF flow must be higher for the same transferred heat flow.

This fact shows, that there is an optimisation potential between the main steam pressure, the final feedwater temperature and the HTF return temperature to the solar field, which is different to conventional steam power plants. In conventional steam power plants a higher final feedwater temperature in any case leads to higher overall efficiencies.

Daily start up and shut down

Besides the above mentioned special CSP features a concentrated solar power plant of course requires several more adaptations compared to conventional steam power plants. For example a solar power plant is a daily start / stop plant. This has to be considered for the turbine design and requires efficient standstill solutions. One aspect is an efficient sealing steam generation over the night period in combination with optimized cooling system for the standstill period, as the sealing steam has to be condensed continuously.

3 Steam Turbine Package

Siemens is developing a steam turbine package SST-PAC 5000 for Concentrated Solar Power plants in the range of 200 MW to above 300 MW. The package consists of a steam turbine, a generator, all necessary auxiliary systems, instrumentation and a control system.

The main innovative component of the SST-PAC 5000 for CSP is the combined HP/IP steam turbine. The generator and the auxiliary systems are taken from the existing product portfolio. Therefore this chapter focuses on the steam turbine.

As mentioned in chapter 2, the steam cycle may optionally be equipped with a second steam reheat before the LP turbine. This requires slight modifications of the LP turbine's inlet, however, the overall design remains identical to LP turbines used for combined cycle or steam power plants.

3.1 Thermodynamic Experience

Siemens has been supplying steam turbines for various applications for over 80 years. Figure 4 shows the range of today's typical steam cycles. Nuclear Power Plants (NPP) typically provide saturated main steam of around 80 bars and 300°C. The wetness at the low pressure (LP) exhaust is around 0.8. State of the art Ultra Supercritical (USC) steam power plants reach main steam temperatures of up to 600°C and main steam pressures up to 280 bars. Here the LP exhaust wetness is around 0.9. CSP plants typically come with a main steam temperature of 380°C at a pressure of 100 bars and LP exhaust wetness of about 0.85. Thus CSP thermodynamic parameters are somewhere in between NPP and USC i.e. CSP steam cycles are well covered by Siemens' range of experience.

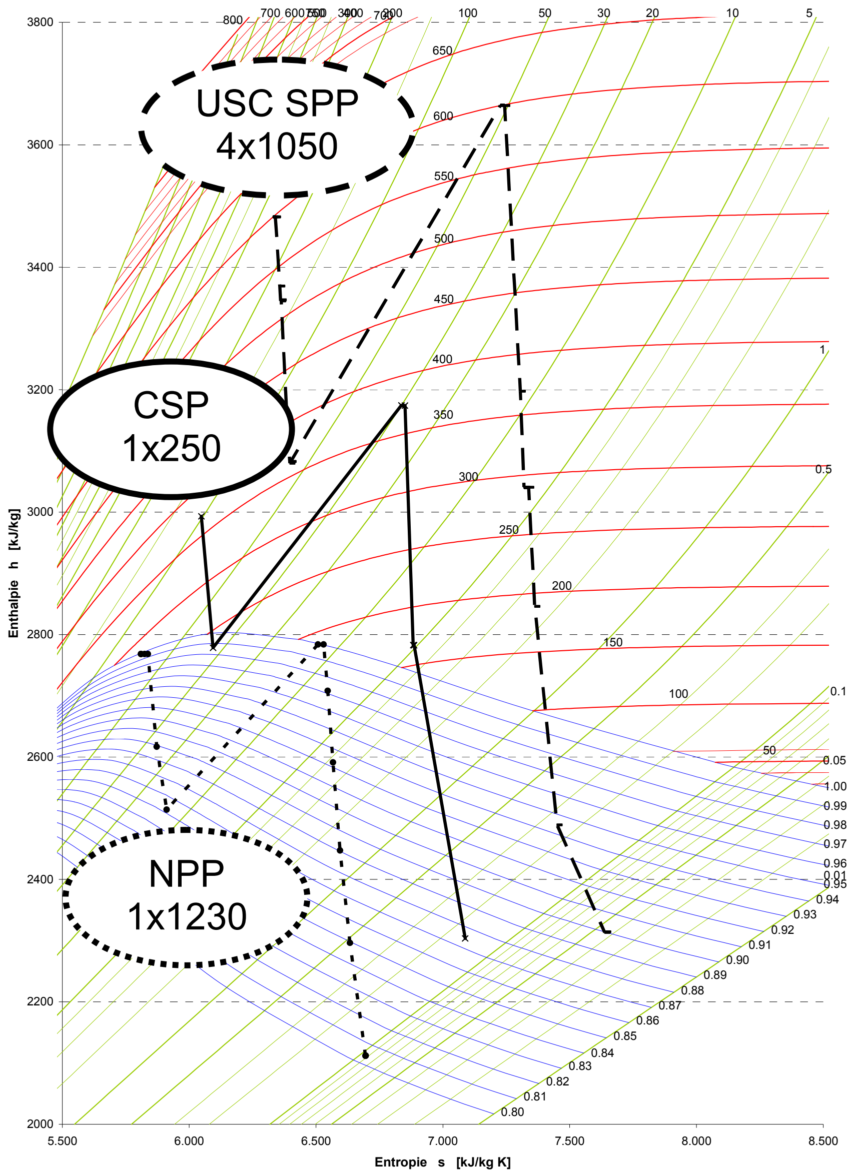

Figure 4: h,s diagrams of different typical steam cycles for Siemens large scale steam turbine applications

3.2 HI Turbine: History, References, Technology

For a power output in a range around 250 MW Siemens typically applies steam turbines of the SST-5000 series as shown on Figure 5. The SST-5000 series steam turbine consists of a combined high pressure (HP) and intermediate pressure (IP) turbine (HI) and a separate LP turbine.

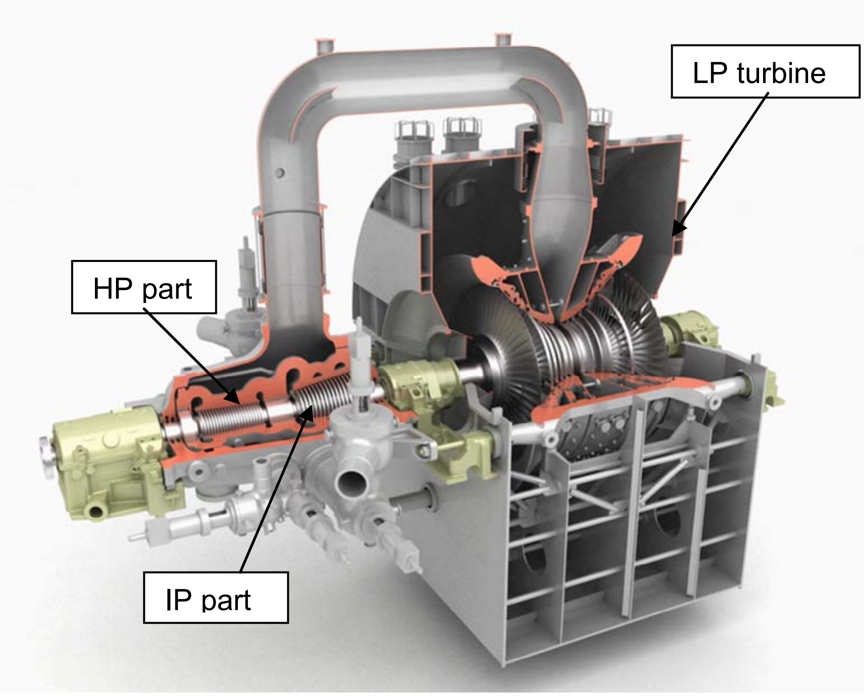

Figure 5: SST-5000 series

The SST-5000 provides options of multiple steam extractions and supports a maximum number of 7 feedwater preheaters.

The design of the HI product family draws on more than 40 years of experience in the development, manufacture and operation of compact, combined turbine modules in over more than 300 applications worldwide. Table 1 shows some of the recent references for combines cycle power plants (CCPP) and steam power plants (SPP). Design features for the HI product family are carefully selected to minimize space requirements and component parts without compromising on efficiency or reliability. All modules in the family are based on the same design philosophy so that proven design features can be progressively applied to all turbines.

All SIEMENS new apparatus HI steam turbines follow the same design principles [1], see Figure 5. The turbine is of double shell design with horizontally-split inner and outer casings. The turbine houses the HP and the IP blade paths as opposed flow sections separated by shaft sealing within one integral inner casing.

The main steam is admitted close to the centre of the turbine. The steam flows through the HP blade path and is routed at the HP exhaust into the cold reheat line. After being reheated, the steam re-enters the turbine again close to the centre and flows through the IP section before exiting the turbine via a single cross-over pipe to the LP turbine.

All HI steam turbines are equipped with high efficiency, variable reaction (3DVTM) drum stage blading. The use of the 3DVTM blading represents the most advanced method of optimizing the high-pressure and intermediate-pressure blading.

The single piece cast steel inner casing is designed using the latest 3D Finite Element Analysis (FEA) techniques and benefits from ribs at top and bottom dead centre of the casing. These equalize the stiffness of the horizontal joint flange, thereby minimizing unsymmetrical casing deformations during operation. All inner casing support and alignment features are designed to enable free thermal expansion from an axial fixed point and radially in all directions.

The bottom half of the casing is attached to the LP inner casing by means of push rods. These couple the expansion of the two components, reducing relative axial expansions in the LP turbine, and thus enabling the selection of enhanced performance LP sealing arrangements. The use of push rods means that sliding bearing pedestals are not required.

All stationary parts are fully integral with the inner casing, reducing the number of parts and therefore the effort for assembly and disassembly. The HI steam turbine can be shipped completely pre-assembled, for rapid erection. The plant balance holes at the outer casing allow easy access to the plant balance weights in the rotor.

The SST-5000 series is characterized by compactness and flexibility of use. This is reflected in the design of the interfaces between the HI steam turbine and the other components supplied as part of the SST-PAC 5000. The HI steam turbine is provided with main steam and reheat steam valves which control the passage of steam into the turbine as shown in Figure 5. One stop and one control valve are combined with an integrated steam strainer in a common casing valve body. The control valve controls the quantity of steam entering the turbine whilst the stop valve is designed to rapidly interrupt the supply of steam as required. To ease access to the inside of the turbine during maintenance, the valve casings are attached directly to the bottom half of the turbine outer casing.

The HI steam turbine is constructed to ensure that axial thrust forces are internally balanced for all operation conditions. In line with the compact design philosophy, the thrust bearing for the rotor train is a combined journal and thrust bearing. This is located in the front bearing pedestal. All bearing pedestals are separated from the turbine casings and are supported directly on the foundation. Only one bearing is located between turbine sections to minimize the effect of foundation deformation on loads to the bearings and shaft journals.

All HI steam turbine modules can be combined with the full range of existing LP modules as required. Different sizes are available and may be configured with down, side, and single-side LP exhaust arrangements.

The existing product portfolio of HI turbines perfectly covers the power class of 250 MW which has been recently requested by customers for large scale CSP projects. However CSP steam parameters differ from typical applications in CCPP and SPP. Generally steam pressure and temperature are lower for CSP and HP exhaust steam may be close to saturated conditions. Therefore Siemens has developed a specific variant of the HI turbine which is optimized for CSP applications. Figure 6 shows the longitudinal cross section of this turbine. Basically the geometry of the steam inlet has been optimized for the reduced main steam pressure (100 bars compared to up to 170 bars for CCPP or SPP). In addition, inner casing, rotor and valve casing materials have been changed due to relatively low main steam temperature (380°C compared to 565°C for most CCPP applications). Finally the HP exhaust section has been modified to withstand possible steam wetness. An internal piping with passive pressure drop prevents wet steam from entering the shaft sealing area. To eliminate remaining risks of erosion corrosion this section of the casing will also be spray coated.

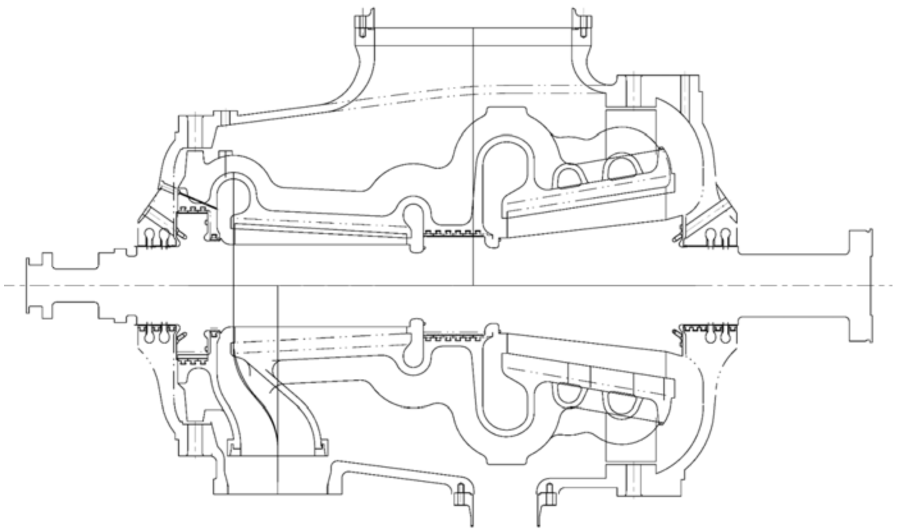

Figure 6: Longitudinal cross section of HI turbine for CSP application

Table 1: Examples of recent references of the SST-5000 series

Plant unit	Country	No. of units	Plant type	Rating [MW]	Speed [s^{-1}]	Commercial operation
Rizhao	China	2	SPP	378	50	1998
Fuzhou	China	2	SPP	382	50	1999
Yangcheng	China	6	SPP	350	50	2000..2002
Hillabee	USA	1	CCPP	306	60	2003
Riverside	USA	1	CCPP	190	60	2004
Yulchon	Korea	1	CCPP	215	60	2005
Köln-Niehl	Germany	1	CCPP	144	50	2006
Becancoure	Canada	1	CCPP	235	60	2007
Herdecke	Germany	1	CCPP	153	50	2007
Summit Lake Side	USA	1	CCPP	246	60	2007
Kaarstoe	Norway	1	CCPP	150	50	2007
Songkhla	Thailand	1	CCPP	267	50	2008
Ca Mau	Vietnam	2	CCPP	263	50	2008
Baosteel	China	1	SPP	350	50	2008
Goreway	Canada	1	CCPP	368	60	2008
Manuel Belgrano	Argentina	1	CCPP	290	50	2009
Sloe Centrale	Netherlands	2	CCPP	154	50	2009
Gent	Belgium	1	SPP	328	50	2010

3.3 Operation and Flexibility

CSP customers are not only focusing on an economical turbine with an excellent heat rate, but also on short start-up times and flexible operation.

With regard to daily cycling, one large (e.g. 1x250 MW) steam turbine has an advantage over two small (e.g. 2x125 MW) steam turbines: The components of large turbines do not cool down as fast as the smaller components of small steam turbines, i.e. the initial temperature difference between steam and metal before start-up is smaller for large steam turbines. In other words: As long as the shut-down time does not exceed 8 to 12 hours, the large steam turbine will not be the critical component for fast start-up of the plant. It also has to be noted that the absolute temperature level of solar turbines (~400° C at 100 bar) is far below the levels of conventional subcritical steam applications (~565° C at 170 bar) – as shown in Figure 4 – thus significantly reducing material fatigue and stress levels.

With regard to high part-load efficiencies, the influence of the cold end must not be under-estimated. At 50% load two small steam turbines have a performance advantage because one turbine could be switched off, leaving the second turbine operating in its optimum nominal point (unlike one big steam turbine, which would have to operate at 50% of its nominal load). But since each turbine has its own condenser, only half the total condenser surface can be utilized if one of two turbines is shut off. This results in a performance disadvantage compared to the 50% load case of one large steam turbine, which has a larger condenser surface and therefore a lower condenser pressure and thus a better efficiency.

Since the requirements for more flexibility have also recently occurred for CCPP, Siemens SST-5000 series is generally optimized with regard to start-up time and operational flexibility.

On the one hand the design of the rotor diameter has been optimized to achieve maximum efficiency and minimum thermal stress i.e. minimum start-up time. On the other hand the start-up procedure for daily cycling has been optimized to enable steam admission as early as possible and thus enable plant hot starts well below 40 minutes. Furthermore the specific turbine design has proven its superior part-load capabilities already for CCPP and SPP applications. As steam temperatures of CSP plants are lower than in CCPP and SPP, part-load performance will be equally high. [2]

4 Summary

Parabolic trough systems are currently the best available technology for CSP plants. The market for these plants is rapidly growing and future projects will have increased plant sizes of more than 200 MW.

Compared to fossil-fired steam power plants, CSP plants require special features like daily cycling, high part-load efficiency and flexible feedwater preheating.

The CSP steam cycle is characterized by rather low temperatures and pressures. Specific challenges are moisture at the turbine exhausts, storage operation and the optimization of the final feed water temperature. Double reheating is a promising option to increase overall thermal performance and to reduce the moisture content.

SIEMENS has customized its well proven combined HI turbine to fully satisfy the described CSP requirements. For an icreased plant size of around 250 MW one large steam turbine has several advantages compared to two smaller turbines.

5 References

[1] Hurd P., Truckenmueller F., Thamm, N., Pollak, H., Neef, M., Deckers, M. Modern Reaction HP/IP Turbine Technology Advances & Experiences, Proceedings of PWR2005, Asme Power, April 2005.

[2] Thamm, N., Mueller, T., Wallis, A., Thiemann, T. Uprating a Proven Design to Meet Today's Requirements – SIEMENS Combined HP/IP Steam Turbine Family, Power Gen Europe 2007

[3] SolarPaces CSP database, http://www.nrel.gov/csp/solarpaces/

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